

Article

Taguchi-Based Experimental Optimization of PET and Bottom Ash Cement Composites for Sustainable Cities

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Abstract

Waste valorization in construction materials offers a promising pathway to reducing environmental burdens while promoting circular resource strategies in the built environment. This study develops a novel composite mortar formulated with sustainable materials and alternative aggregates, namely polyethylene terephthalate (PET) particles recovered from post-consumer plastic waste and bottom ash from thermal power generation. Natural pumice was incorporated to improve the lightness and the thermal insulation, with cement serving as the binder. The mix design was systematically optimized using the Taguchi method to enhance performance while minimizing carbon emissions. The resulting mortar, produced at both laboratory and small-scale commercial levels, demonstrated favorable technical properties: dry density of 1.3 g/cm³, compressive strength of 5.96 MPa, thermal conductivity of 0.27 W/(m·K), and water absorption of 16.1%. After exposure to 600 °C, it retained 60.6% of its strength and exhibited only a 10.1% mass loss. These findings suggest its suitability for non-load-bearing urban components where sustainability, thermal resistance, and durability are essential. The study contributes to global sustainability goals, particularly Sustainable Development Goal (SDG) 11, 12, and 13, by illustrating how waste valorization can foster resilient construction while reducing the environmental footprint of cities.

Keywords: composite materials; sustainable development goal; sustainable materials; Taguchi method; waste valorisation



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1. Introduction

Improper disposal of untreated waste causes environmental pollution, land degradation, and health risks [1–3]. Replacing natural aggregates with waste-based materials supports sustainability and resource efficiency [4–6]. Concrete, the most consumed building material after water, consists of about 70% aggregates by volume [7,8], making waste incorporation an environmental necessity.

Recycling waste as aggregate or binder in cement composites is an energy-efficient method [9]. Cement-based composites are popular due to cost-effectiveness, ease of shaping, and architectural adaptability [5]. The growing use of alternative materials in construc-

tion reduces cement consumption, improving waste management and lowering carbon and water footprints.

New energy efficiency standards aim to cut energy use and carbon dioxide (CO₂) emissions from buildings nearly to zero [10]. The cement industry accounts for 25% of industrial CO₂ emissions and 7–8% of global emissions. Global monitoring and regulations target emission reductions [11]. Thus, efforts focus on creating building materials that use less cement—a major CO₂ source—and incorporate waste to save natural resources and energy.

Waste additives enhance mechanical properties, reduce costs, and decrease CO₂ emissions [12]. High density of conventional concrete has led to an increased demand for lightweight waste aggregates [13]. Since 2013, research on bottom ash, fly ash, and PET waste as aggregates has surged.

Plastic waste production for cementitious materials is rising steadily, with projections exceeding 20 million megatons of resin by 2050 [14]. Since the 1950s, plastic accumulation across land and oceans has caused blockages, soil contamination, and air pollution due to its non-biodegradability, leading to a global crisis [15,16].

Plastic is an underused resource with potential for valuable transformations [17]. Despite regional differences in accumulation [18], plastic consumption continues to grow, especially in developing countries, with about 60% turning into waste [19]. Without intervention, landfills may hold around 1 billion tons of plastic waste by 2050 [16]. Currently, only about 25% of plastic is recycled, while the rest is landfilled or openly burned, contributing to pollution [18,20]. Inefficient recycling technologies strain ecosystems [21]. Thus, recycling remains a key strategy to reduce plastic waste and its environmental impact [22].

Plastic waste remains a major environmental concern due to its persistence in nature [23]. Using recycled plastic as aggregate can save about 820 million tons of sand annually 5% of global demand [24]. Properly designed mixtures maintain structural integrity [25]. In addition, PET inclusion improves acid resistance, reduces weight, and decreases fine aggregate demand [26]. Adding 1% PET raises compressive strength by 58% and flexural strength by over 23%, whereas 1–3% PET may produce varied effects [27,28], though excessive amounts may reduce performance [16]. Approximately 70 million tonnes of PET are produced yearly, making up 12% of global solid waste [29,30]. This study proposes combining PET waste with thermal power plant bottom ash to produce structural concrete blocks.

Coal-fired power plants generate large waste volumes, posing environmental challenges. Coal accounts for 30% of global primary energy and 41% of electricity, with expected growth in electricity generation over 50% by 2030 [31]. Combustion produces ash, often dumped in landfills or water bodies [32]. Fly ash and bottom ash form 15% of total global ash [33]. When used in cementitious materials, they provide environmental and economic benefits [34,35]. Bottom ash shares geological traits with natural sand and is a cost-effective alternative in briquette and mortar production [32,36]. Bakoshi et al. [37] showed that increasing the proportion of fine aggregates replaced by bottom ash improves both the compressive and tensile strength of concrete. However, while concrete produced with bottom ash exhibited lower freeze–thaw resistance than reference concrete, it showed superior abrasion resistance [37,38]. Additionally, construction materials produced with bottom ash have been observed to be fire-resistant [39]. Substituting up to 40% of sand with bottom ash has minimal impact on mortar strength [2]. Coal waste-based blocks may provide net environmental benefits [40].

Natural aggregates like pumice also contribute positively, reducing concrete weight by 17% and improving freeze–thaw resistance [41]. According to Web of Science studies,

the Taguchi method is widely used to optimize waste-based mortars, efficiently balancing cost and performance.

Recent studies emphasize the increasing interest in sustainable cement-based composites with waste or alternative cementitious materials to reduce environmental impact. For example, Ijaz et al. [42] provide a comprehensive review of limestone calcined clay cement (LC3), exploring how pozzolanic additives influence hydration mechanisms, mechanical behavior, high-temperature durability, and environmental benefits in both lifecycle and micro-macro scales. Likewise, research on extrusion-based 3D concrete printing has shown that incorporating cellulosic materials, supplementary cementitious materials, and waste aggregates can significantly impact workability, thermal insulation, and long-term performance [43]. These findings support the rationale for investigating waste PET, bottom ash, and pumice combinations in this study, especially in terms of balancing lightweight and thermal performance with mechanical strength and durability.

This study explores using PET and bottom ash as alternative construction materials to reduce cement use and CO₂ emissions. Nine composite mortar mixtures were optimized via Taguchi design and tested for mechanical, physical, thermal, and environmental properties, aiming to produce sustainable, cost-effective structural blocks comparable to traditional materials.

2. Materials and Methods

As shown in Figure 1, acidic pumice (Isparta), bottom ash from a thermal power plant (Kütahya), and PET waste (<4 mm, Istanbul) were used for composite optimization in this study. The particle size distribution of PET waste was determined by sieve analysis, and the results are presented in Table 1. Most of the PET particles were in the 2–8 mm range, and the calculated average particle size was approximately 3–4 mm. This grading is considered important since particle size can influence both porosity and strength of the composite.

CEM I 42.5 R cement (TS EN 197-1:2002) [44], from local Portland cement supplier, was used as the binder, and tap water from Antalya was used for mixing. Table 2 presents the chemical compositions of the bottom ash and cement. The bottom ash contained Reactive CaO (9.51%) and Reactive SiO₂ (22.46%), which can participate in secondary hydration and pozzolanic reactions with cement. Reactive CaO contributes to the formation of additional calcium silicate hydrate (C–S–H), while Reactive SiO₂ reacts with Ca(OH)₂ released during cement hydration, further enhancing the pozzolanic activity. These reactions densify the microstructure, reduce porosity, and improve long-term durability [45–47]. This chemical composition was one of the key reasons for selecting bottom ash in this study.



Figure 1. The materials used in the study, from right to left, are pumice, bottom ash, and PET.

Table 1. Particle size distribution of PET particles.

Sieve Size (mm)	Retained (%)	Passing (%)
16.0	0.40	100
8.0	14.3	85.7
4.0	45.9	39.7
2.0	59.4	40.3
1.0	35.1	5.23
0.5	5.00	0.24
0.25	0.24	0.00
Pan	0.00	0.00
Total	100	100

Table 2. Chemical composition of cement and bottom ash utilized in the study.

Chemical Composition	Materials	
	Cement (%)	Bottom Ash (%)
SiO ₂	20.5	48.6
Al ₂ O ₃	4.65	16.1
Fe ₂ O ₃	3.40	5.82
MgO	2.03	2.82
Na ₂ O	-	0.49
CaO	68.7	16.9
P ₂ O ₅	0.08	2.28
SO ₃	2.20	2.02
Loss on Ignition (LOI)	-	0.87
Reactive CaO	-	9.51
Reactive SiO ₂	25.7	22.5
Free CaO	-	<0.01
Chloride (Cl ⁻)	0.02	0.01

The specific gravities were 3.11 for cement, about 0.9 for bottom ash, and 0.7 g/cm³ for pumice. The water absorption rates were measured as 38.17% for bottom ash and 24.77% for pumice. Before proceeding with the experimental studies, the granulometry of the materials was determined to facilitate the Taguchi design process. A granulometric curve graph was created, as shown in Figure 2. In this figure, the y-axis represents the total percentage passing (%) and the x-axis represents the sieve size (mm). The curves correspond to different particle size distribution models: “Upper” and “Lower” indicate the boundary limits of grading, “Middle” represents the average grading line, “Fuller” refers to the theoretical Fuller curve, and “Mixture” shows the particle distribution of the prepared mix. These curves were used to evaluate the compatibility of the experimental mixture with standard grading ranges.

The Taguchi Design Method (TDM) was used to optimize mortar mixes incorporating waste, aiming to meet standard performance criteria. Experimental variables and performance metrics were evaluated within this framework. The selected parameters and their levels are shown in Table 3.

Using the levels in Table 3, an L9 Taguchi orthogonal array was formed with three parameters—cement content, pumice/bottom ash ratio, and PET percentage—each at three levels. The control factors and levels used in the Taguchi L9 design were determined based on both literature review and preliminary trials carried out in this study. Cement contents of 250, 275, and 300 kg/m³ were selected, as this range reflects the values commonly used in lightweight, non-load-bearing construction materials. Below 250 kg/m³, the binder content becomes insufficient and durability decreases, while values above 300 kg/m³

raise cost and carbon emissions without a proportional improvement in performance. Pumice/bottom ash ratios of 30/70, 40/60, and 50/50 were chosen to examine the balance between pumice, which improves lightness and thermal insulation, and bottom ash, which enhances density and contributes to pozzolanic activity. Previous studies have shown that the fineness of bottom ash strongly affects both water absorption and strength development [48]. For this reason, the bottom ash content was not taken beyond 70%. The intermediate levels were included to observe how changes in the balance between the two aggregates influence overall behavior. PET contents of 4%, 7%, and 10% were set according to both the literature and our preliminary observations. Previous studies reported that PET additions above 10% often lead to severe reductions in strength and workability, or even material disintegration at high temperatures [49,50]. In contrast, very low PET contents (1–3%) showed positive effects on strength but are less representative for structural-scale applications [27,51]. Therefore, the intermediate levels of 4%, 7%, and 10% were selected to balance practical feasibility, mechanical performance, and thermal insulation potential, while remaining within the limits recommended in the literature [52]. In summary, the selected ranges are consistent with both previous studies and our own preliminary tests, and they represent practical parameter levels that balance strength, lightness, and thermal insulation. The details of the control factors and their levels are given in Table 3.

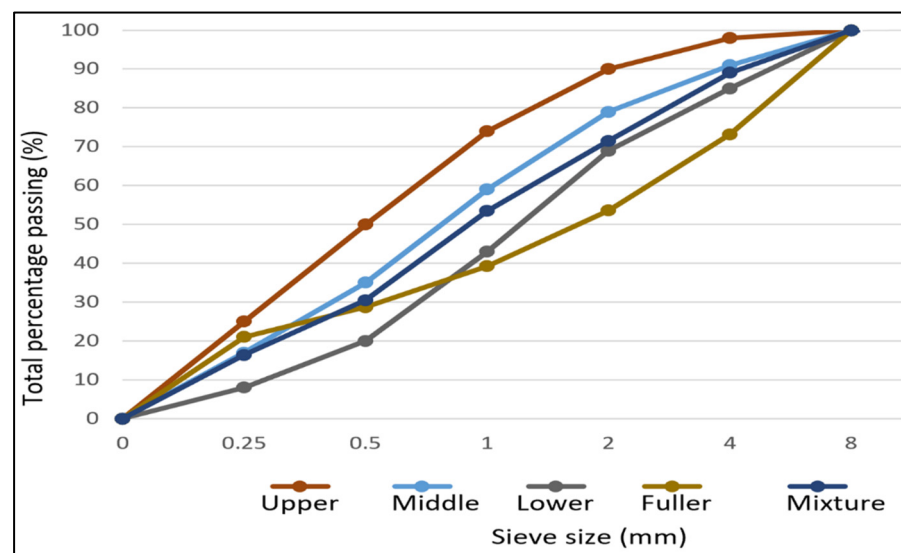


Figure 2. Granulometry curve of materials before Taguchi.

Table 3. Parameters and levels used in the Taguchi design.

Parameters	Levels		
	1	2	3
Cement (kg/m ³)	250	275	300
Pumice/Bottom Ash (% by volume)	30/70	40/60	50/50
PET (% by binder weight)	4	7	10

Nine mortar mixes with varying material proportions were prepared to develop waste-based building blocks. The experimental plan is shown in Table 4. The Taguchi method guided the optimization of these mixtures based on the chosen parameters.

Table 4. Selected L9 (33) experimental design plan.

Types	Cement (kg/m ³)	Pumice/Bottom Ash (%)	PET (%)
1	250	30/70	4
2	250	40/60	7
3	250	50/50	10
4	275	30/70	7
5	275	40/60	10
6	275	50/50	4
7	300	30/70	10
8	300	40/60	4
9	300	50/50	7

A specially designed block press machine (Figure 3) was developed to simulate pilot-scale industrial production and was used for all specimen fabrication. The device consists of lower and upper molds, a feed tray, a pressing mechanism, and an electrical control unit. Both the upper and lower molds are equipped with electric motors that provide vibration during compaction. The system applies to a theoretical load of approximately 20 kg and produces a maximum vibration force of 1.96 kN.

**Figure 3.** Photograph of the building block compression machine.

For each of the nine Taguchi-designed mixtures, raw materials (cement, pumice, bottom ash, and PET) were first pre-dried under natural outdoor conditions and sieved before use. The mix proportions were weighed according to the design formulations, and materials were added sequentially from finer to coarser fractions. PET particles were introduced at the designated percentages, followed by the gradual addition of water while continuously mixing. Mixing was carried out manually and then continued for about 5 min in a vertical mechanical mixer to achieve homogeneity.

The fresh mortar was manually placed into molds, positioned in the press, and subjected to vibration simultaneously from the upper and lower mold sections for approximately 20 s. Surface levels were checked, deficiencies were refilled, and the top surfaces were leveled. Immediately after, the specimens were demolded and prepared for curing.

Table 5 lists test methods, standards, specimen sizes, and quantities. A total of 189 samples were tested and cured using standard moisture-sealing procedures. The set of specimens obtained for each type is presented in Figure 4.

Table 5. Test methods, standards, and specimen details.

Test Type	Standard	Specimen Size (mm)	Number of Sets per Formulation	Total Number of Specimens
Compressive Strength (28 days)	TS EN 1015-11:2000 [53]	100 × 100 × 100	6	6 × 9 = 54
Water Absorption and Capillarity	EN 1015-18:2004 [54]	100 × 100 × 100	3	3 × 9 = 27
High-Temperature Resistance	—	50 × 50 × 50	9	9 × 9 = 81
Thermal Conductivity	EN 12664:2009 [55]	300 × 300 × 50	3	3 × 9 = 27
Total	—	—	—	189

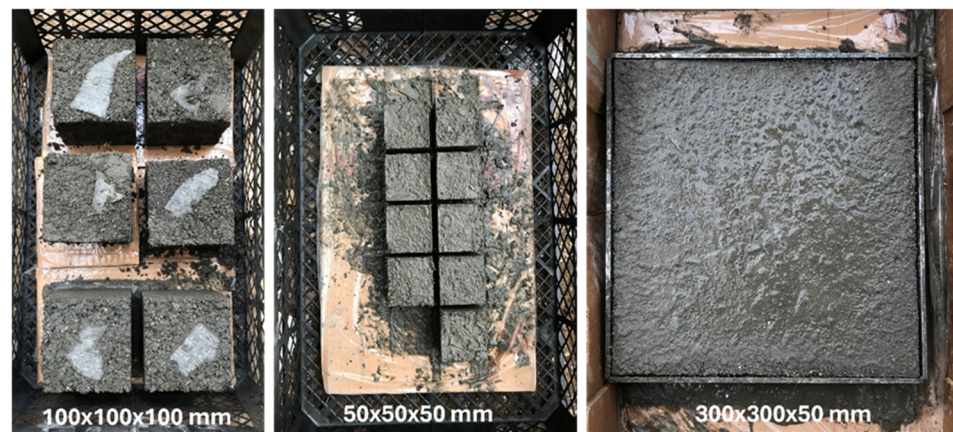


Figure 4. The set of specimens obtained for each type.

Compressive strength tests were performed in 28 days on 100 × 100 × 100 mm cube specimens from nine mortar mixes, with three samples per mix. Samples were cured in water for 72 h, weighed in saturated surface-dry condition, then oven-dried at 60 ± 5 °C for 72 h to determine moisture content. Water absorption, void ratio, and dry unit weight were calculated then followed by capillary water absorption tests.

For each mix, three 300 × 300 × 50 mm specimens were oven-dried at 105 °C for 24 h after 28 days of curing and then tested for thermal conductivity using a Hot Plate device. For the high-temperature durability tests, nine sets of 50 × 50 × 50 mm specimens were prepared for each mixture. After 28 days of curing, the specimens were oven-dried at 105 °C for 24 h and then tested in a muffle furnace. For each mix, three sets of specimens were subjected to a stepwise heating regime: the temperature was increased by 200 °C every 30 min, reaching 600 °C in 1.5 h, 800 °C in 2 h, and 1000 °C in 2.5 h. The specimens were then kept at the target temperature for an additional 3 h before the furnace was opened and cooling was allowed under ambient air [56].

All specimens were weighed before and after furnace exposure to determine weight loss, while compressive strength loss was calculated. These procedures were designed to simulate fire exposure and to evaluate the thermal stability of cement-based composites containing bottom ash and PET. Cost and CO₂-equivalent (CO₂-e) emission calculations were conducted for 1 m³ of composite mortar mixture. In selecting structural elements, cost is an important factor alongside technical properties. For the nine mortar mixtures

studied experimentally, cost calculations included only raw material expenses (bottom ash, PET, pumice, cement, water) based on June 2023 prices, excluding logistics, machinery, and labor. CO₂-e emissions were calculated solely from the mortar components, excluding production and logistics emissions. Reference emission values used were: cement CEM-1 at 930 kg-CO₂/ton (UK) and 1165 kg-CO₂/ton (Turkey) [57]; bottom ash and pumice at 4 kg-CO₂/ton (UK) [58]; water at 0.3 kg-CO₂/ton (UK); recycled PET (r-PET) at 1.76 kg-CO₂/kg and virgin PET at 2.15 kg-CO₂/kg [59]. PET recycling offers energy savings, reflected by an emission of −3.38 kg-CO₂/kg [60,61]. Additionally, when reviewing new technology-based PET recycling methods, the ALPLA PET Recycling Team reported a 79% improvement, reducing r-PET emissions to 0.45 kg-CO₂/kg [59]. This study used −0.45 kg-CO₂/kg as PET's reference emission, considering recycling gains and recent data. CO₂-e calculations for all mixtures applied these literature-based values.

Performance characteristics and signal-to-noise ratios were analyzed using the Taguchi Design Method (TDM). Relevant formulas and details are in Table 6 [62].

Table 6. Taguchi performance characteristic formulas of investigation [62].

Performance Characteristic	Performance Attribute	Formula	Explanation
"Bigger is better."	Compressive Strength	$\frac{S}{N_i} = -10 \log x \left[\frac{1}{N_i} \sum_{u=1}^{N_i} \frac{1}{Y_u^2} \right]$	i: Experiment number u: Trial number N _i : Number of trials conducted for the i-th experiment
"Smaller is better."	Dry unit weight, Water absorption, Capillary water absorption, Thermal conductivity, Pressure and weight loss after high temperature, Cost and carbon dioxide emissions	$\frac{S}{N_i} = -10 \log x \left[\sum_{u=1}^{N_i} \frac{Y_u^2}{N_i} \right]$	y: Desired mean value yu: Measured value of each observation

3. Results and Discussion

The experimental results of the nine specimen types designed using the Taguchi Method are summarized in Table 7. Average values from replicate specimens were used for all tests. Detailed experimental data, excluding cost and CO₂ calculations, are presented in the table.

Strength loss results are shown in Table 7 for 600 °C. Depending on the mixture, the reduction in compressive strength varied between 42% and 75%. Although strength data for 800 and 1000 °C were not measured in this study, similar trends are expected, with further reductions due to progressive microstructural degradation. This will be considered in future studies to complete the long-term high-temperature performance evaluation. Cost and CO₂-equivalent data calculated for 1 m³ composite mortar are summarized in Table 8.

From a chemical standpoint, PET is an inert material that does not undergo hydration or pozzolanic reactions within the cementitious matrix. Instead, its contribution is primarily physical, acting as a lightweight aggregate that modifies pore distribution and reduces thermal conductivity. However, this inert nature also means that the interfacial transition zone (ITZ) between PET particles and the cement paste is relatively weak compared to mineral aggregates, which can negatively influence long-term durability. The addition of bottom ash and pumice, which contain reactive silica and calcium compounds, partially compensates for this limitation by enhancing the overall matrix densification and improving the bond around PET particles. These interactions explain the observed balance between lightweight properties, thermal insulation, and mechanical strength in the proposed composite [63–66].

Table 7. Experimental results of nine different mixtures.

Mixture No		1	2	3	4	5	6	7	8	9
28-day Compressive Strength (MPa)		6.33	7.37	5.96	4.89	9.27	10.80	8.82	12.40	10.30
Unit Weight in Water (g)		571	583	541	555	569	619	540	640	642
Saturated Surface Dry Weight (g)		1558	1556	1509	1520	1554	1605	1510	1633	1628
Dry Unit Weight (g/cm ³)		1.32	1.33	1.30	1.34	1.33	1.34	1.36	1.46	1.48
Water Absorption (%)		18.00	16.70	16.10	13.60	16.40	19.50	14.40	12.10	9.88
Void Ratio (%)		24.10	22.80	21.60	18.90	22.20	26.60	19.60	17.70	14.90
Thermal Conductivity Coefficient (W/(m·K))		0.28	0.28	0.27	0.30	0.31	0.31	0.32	0.39	0.41
Strength Loss at 600 °C (%)		42.40	52.20	60.60	54.50	70.50	67.90	58.40	64.60	75.10
Measurement Time (Minutes) Water Absorption Percentages %	15 min	0.64	1.70	2.93	1.64	2.08	1.17	1.43	1.12	0.74
	60 min	1.07	2.29	3.59	2.30	2.81	1.72	1.98	1.79	1.24
	240 min	2.05	3.07	4.52	3.23	3.88	2.69	2.91	2.79	1.95
	1440 min	4.48	4.84	6.55	5.34	6.21	5.00	4.80	4.77	3.23
Capillarity Coefficient (g/cm ²)	15 min	8.63	22.73	38.16	22.00	27.84	15.76	18.97	16.46	10.95
	60 min	14.37	30.67	46.77	30.9	37.55	23.26	26.28	26.21	18.39
	240 min	27.59	41.07	58.97	43.4	51.9	36.26	38.53	40.85	28.93
	1440 min	60.32	64.71	85.45	71.73	83.02	67.42	63.68	69.75	48.00
Weight Loss (%)	600 °C	8.70	10.70	10.10	10.30	12.10	8.30	11.80	7.90	9.80
	800 °C	12.50	14.70	16.80	14.00	17.30	12.10	16.50	11.50	13.40
	1000 °C	15.20	18.00	19.80	17.60	19.30	15.40	19.60	14.20	17.30

Table 8. Cost and carbon dioxide equivalent results.

Mixture No	1	2	3	4	5	6	7	8	9
Unit Cost (\$)	30.28	31.23	32.17	33.82	34.65	32.76	37.24	35.35	36.29
Carbon Dioxide Emission (kg CO ₂ -e/m ³)	235	226	218	251	243	259	267	284	276

3.1. Compressive Strength

The 28-day compressive strengths, evaluated via Taguchi's "larger is better" S/N ratios, increased with higher cement content, as shown in Figure 5. The optimal mix had a 40/60 pumice/bottom ash ratio and the lowest PET content. Differences between 40/60 and 50/50 ratios diminished over time. PET content above 1% reduced strength, aligning with prior findings: Bai et al. [67] reported that bottom ash up to 30% had no negative effect on long-term strength; Konak [68] linked higher bottom ash to increased porosity and lower strength; Demirel and Keleştemur [69] found that pumice improves strength over time; Akinyele et al. [49] observed that PET content under 5% enhances strength, but higher content reduces it. In this study, the mechanical and durability tests were conducted at 7 and 28 days, which are widely adopted reference ages in cement-based composite research. Although longer curing times were not included in the experimental program, previous studies have demonstrated the continued pozzolanic activity of bottom ash beyond 28 days. For example, Jaturapitakkul and Cheerarot [70] reported that mortars containing 20–30% ground bottom ash as cement replacement exhibited lower compressive strength than plain mortar at early ages but surpassed the control strength after 60 days due to enhanced pozzolanic reactivity. Similarly, when 20% of cement was replaced with ground bottom ash, the compressive strength at 60 days exceeded that of mortars with higher cement content. These findings confirm the potential of bottom ash to improve long-term strength, supporting the expectation that the mixtures developed in this work may also continue to gain strength beyond 28 days.

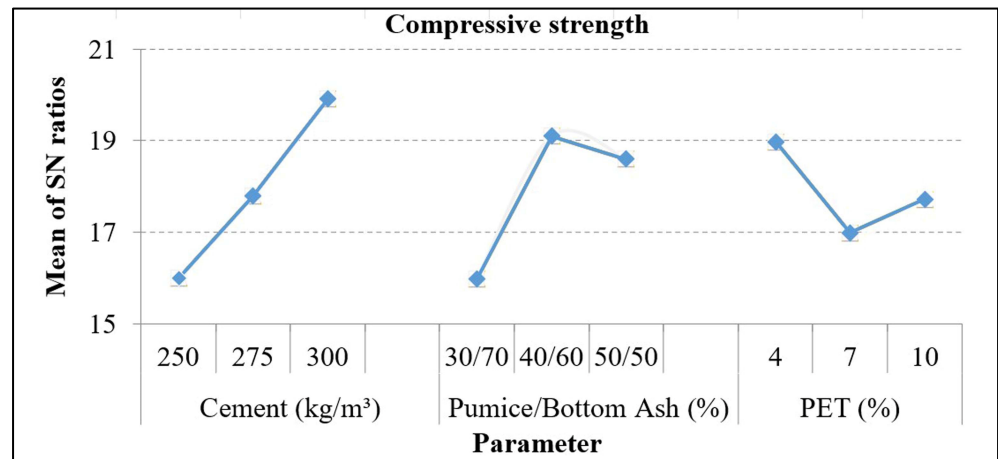


Figure 5. The impact of various parameters on the performance metrics of the 28-day compressive strength of specimens.

3.2. Dry Unit Weight

Dry unit weights were analyzed using Taguchi's 'smaller is better' S/N ratios. As shown in Figure 6, reducing cement and increasing PET improved performance by lowering density. A higher bottom ash ratio raised the unit weight due to its lower porosity compared to pumice. Lightweight PET particles and porous bottom ash reduced overall product weight. Similar trends were noted by Akçaözöğlu et al. [71]. Yüksel et al. [32] reported a 40% unit weight reduction using bottom ash. Bottom ash and pumice are widely used as lightweight aggregates in Europe [40,72,73].

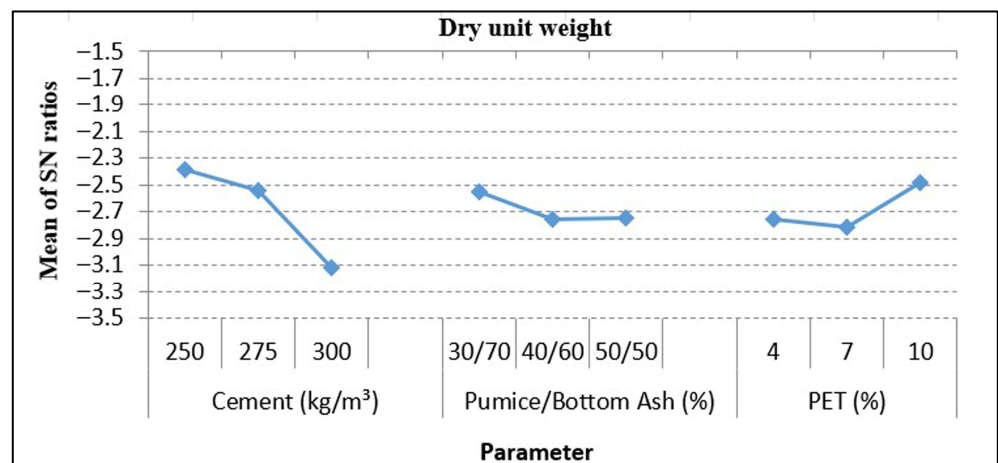


Figure 6. The effect of parameters on the performance statistics of the dry unit weight results of the specimens.

3.3. Water Absorption

Water absorption was evaluated using Taguchi's "smaller is better" S/N ratio. As shown in Figure 7, increasing cement and using a 50/50 pumice–bottom ash ratio improved performance. Although PET is hydrophobic [54], the best result was at 7% PET, while lower percentages of PET resulted in poor performance. Similar trends were noted by Akçaözöğlu et al. [71]. Bai et al. [67] found that higher bottom ash increased water absorption.

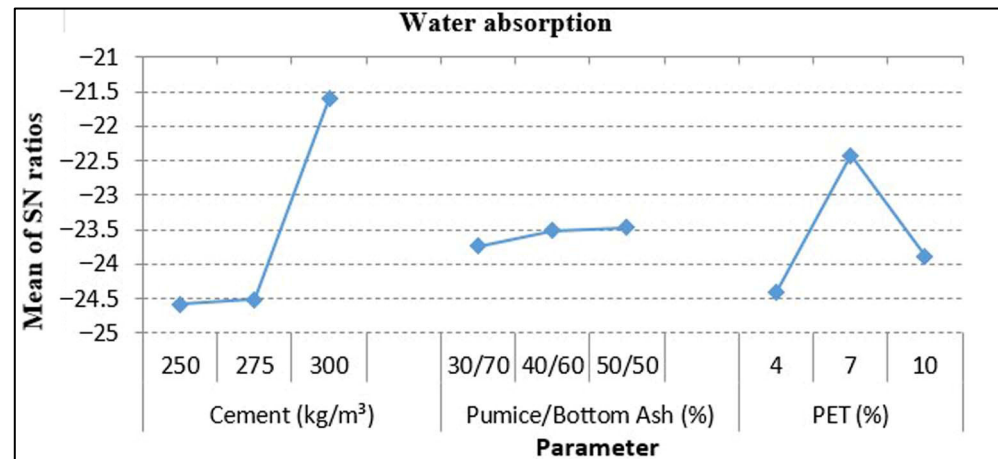


Figure 7. The effect of parameters on performance statistics based on the variance analysis results of the water absorption of the specimens.

3.4. Capillarity Absorption Coefficient

Capillarity absorption coefficient values were evaluated using Taguchi's "smaller is better" S/N ratios. As shown in Figure 8, a higher cement content improved performance. The 40/60 pumice/bottom ash ratio gave the weakest result, while 30/70 and 50/50 results were similar. Although high PET reduced performance, 7% PET yielded the best result, consistent with water absorption trends.

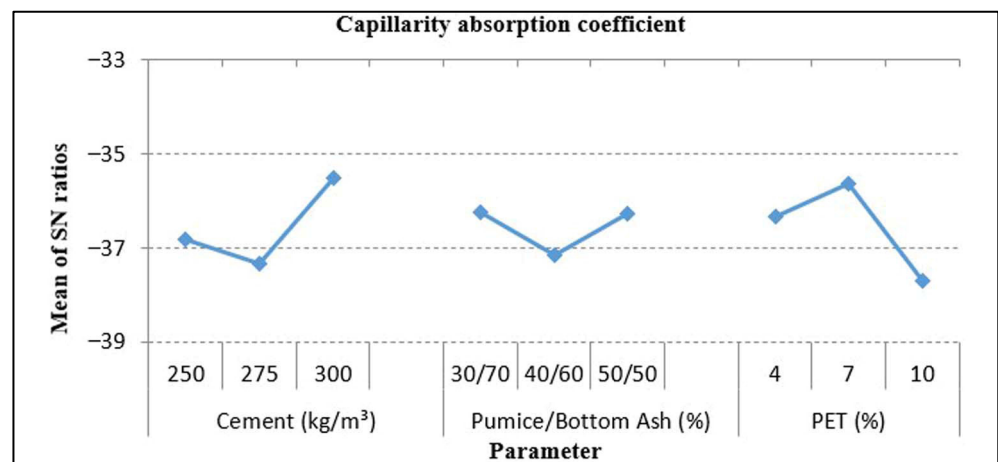


Figure 8. The influence of parameters on the performance statistics from the variance analysis results of the capillarity absorption coefficient for the specimens.

3.5. Thermal Conductivity

The thermal conductivity of the nine mixtures was assessed using Taguchi's "smaller is better" S/N ratios. As shown in Figure 9, increasing bottom ash and pumice content—due to their porous structures—reduced thermal conductivity [74,75]. Likewise, pumice—owing to its porous structure—enhances insulation performance by decreasing thermal conductivity as its proportion increases. The results also suggest that reducing cement content improves thermal insulation and that an optimal balance between pumice and bottom ash yields the most favorable results. Moreover, a higher proportion of PET was found to contribute positively to thermal insulation by filling internal voids within the blocks. This observation aligns with previous research, which found that bottom ash lowers thermal conductivity [40]. Torkittikul et al. [75] further supported these findings by reporting a significant reduction in thermal conductivity with increased coal bottom

ash content. Gündüz and Uğur [76] demonstrated that pumice aggregate concretes exhibit thermal conductivity values of 2.5 to 4 times lower than those of conventional normal-weight concretes.

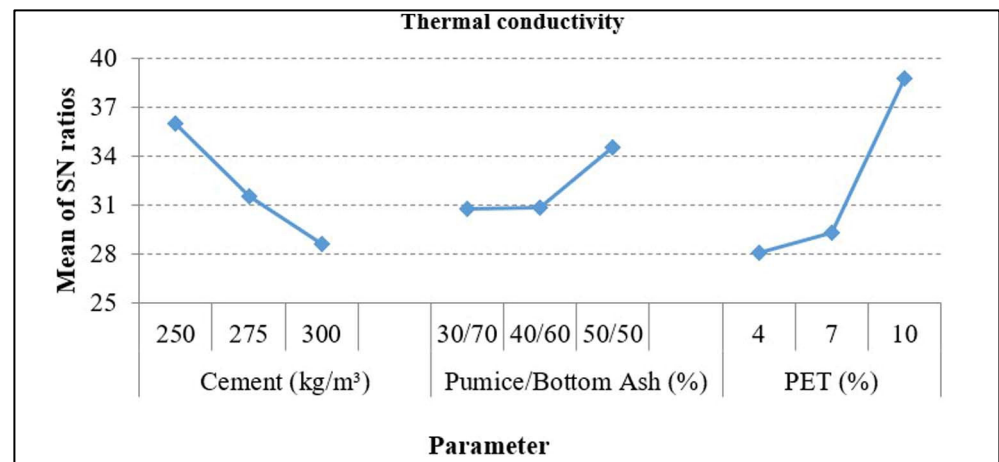


Figure 9. The influence of parameters on the performance statistics from the variance analysis of the thermal conductivity for the specimens.

3.6. High-Temperature Weight and Strength Loss

Weight loss at 600 °C for the nine mixtures was evaluated using Taguchi's "smaller is better" S/N ratios. As shown in Figure 10, higher cement content improved resistance to thermal weight loss. The optimal performance occurred at a balanced pumice/bottom ash ratio, with minimal variation across other ratios. Increased PET content reduced block weight but led to greater loss due to PET melting at high temperatures.

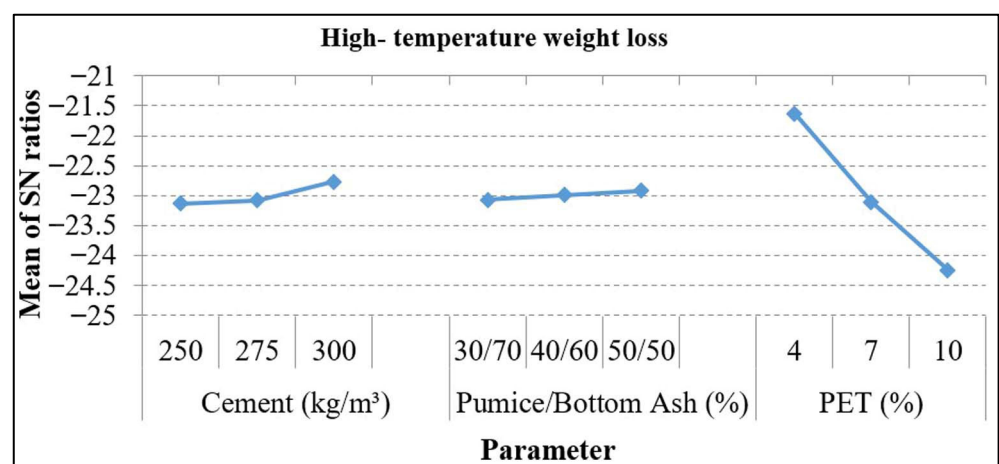


Figure 10. The influence of parameters on the performance metrics derived from the high-temperature weight loss results at 600 °C for the specimens.

Strength loss at 600 °C was assessed for nine mixtures using Taguchi's "smaller is better" S/N ratios. Figure 11 shows that higher cement content increased strength loss, while more bottom ash improved thermal resistance. Increased PET reduced performance. Akinyele et al. [49] found that high PET content caused disintegration, while lower amounts led to edge deformation. Arenas et al. [40] reported enhanced fire resistance due to the expansive evaporation surface of bottom ash. Similarly, Mboya et al. [77] observed that concrete with 10% scoria and pumice exhibited greater compressive strength after exposure to 600 °C than standard Portland cement concrete.

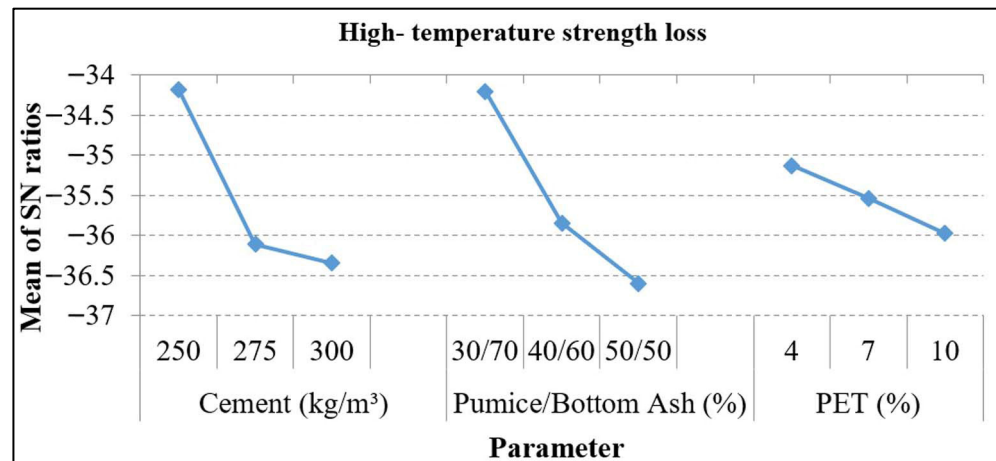


Figure 11. The influence of parameters on the performance metrics derived from the high-temperature strength loss results at 600 °C for the specimens.

3.7. Cost Analysis

Unit costs of nine mixes were evaluated using Taguchi's "smaller is better" S/N ratios. Figure 12 shows that lowering cement content improves cost performance, while the pumice/bottom ash ratio has little effect. Increasing PET reduces cost by lowering aggregate demand despite a slight performance drop. Marzouk et al. [78] showed that shredded PET effectively replaces sand, producing stable, low-cost composites that reduce plastic waste. Bottom ash is more cost-effective than natural sand [32], and pumice offers economical lightweight concrete options [79].

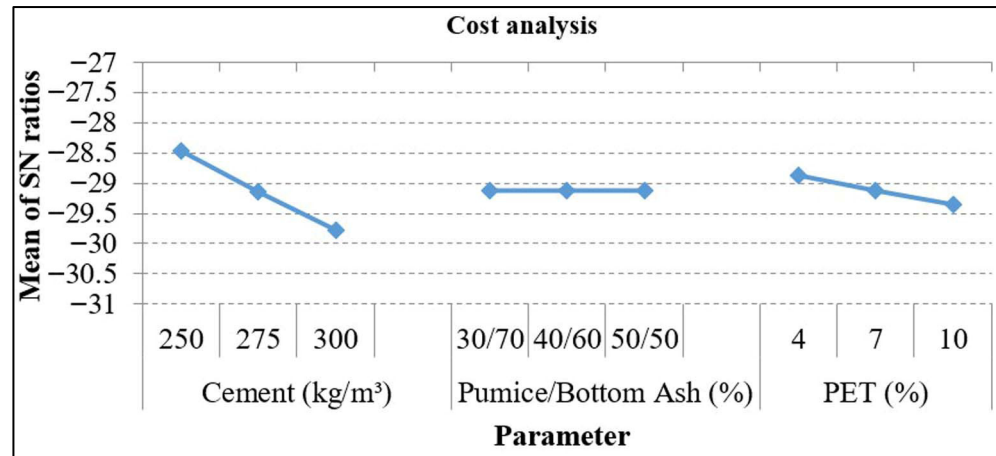


Figure 12. The influence of parameters on the performance metrics of the cost analysis for the samples.

It should be noted that the present cost analysis only considered raw material costs (cement, bottom ash, pumice, and PET) and did not include expenses associated with logistics, machinery use, energy consumption, or labor. Therefore, the reported values represent indicative material-level costs rather than full commercial production expenses. In practice, large-scale production would also be influenced by transportation distance, regional labor rates, and energy prices. A more comprehensive evaluation could involve cost modeling at different production scales and benchmarking against conventional cement-based blocks using full life-cycle cost assessments. Future work will aim to expand the cost analysis to capture these factors and provide a more robust economic comparison.

3.8. Carbon Dioxide Equivalent ($\text{CO}_2\text{-e}$) Emissions

CO_2 emissions per m^3 of nine mixtures were evaluated using Taguchi's "smaller is better" S/N ratios. Figure 13 shows that lowering cement content significantly reduces emissions, while the pumice/bottom ash ratio has little effect. Increasing the PET ratio slightly improved performance, though PET use is associated with higher emissions due to processing, despite being recycled. Still, replacing cement with PET or bottom ash significantly lowers overall CO_2 emissions. Mohammed et al. [80] emphasized the environmental benefits of using PET and bottom ash, while Mboya et al. [77] reported pumice's effectiveness in reducing emissions and addressing climate concerns.

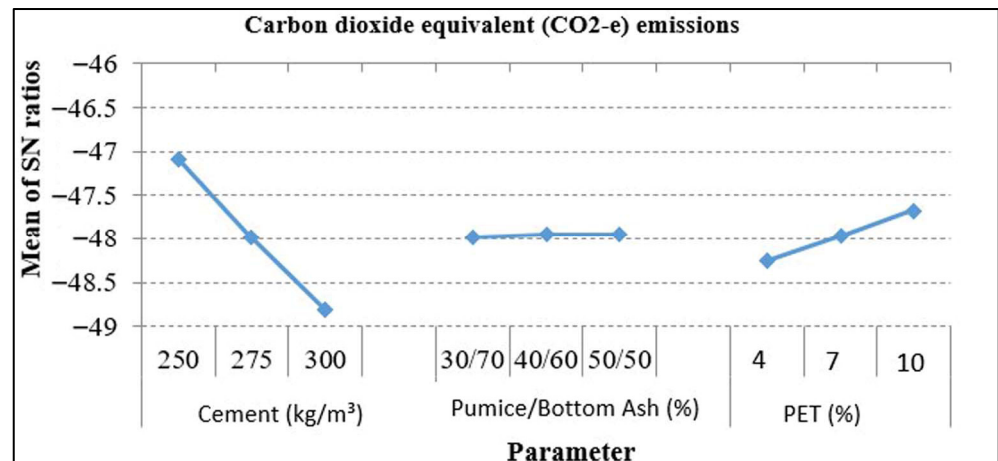


Figure 13. The impact of parameters on the performance metrics derived from the carbon dioxide equivalent emissions of the nine different mixtures.

3.9. Statistical Validation (ANOVA Results)

To evaluate the statistical significance of the observed results, an ANOVA analysis was performed on the experimental data. The findings indicated that at 7 days, both cement content and the pumice/bottom ash ratio had a statistically significant effect on compressive strength ($p < 0.05$), whereas PET content did not show a significant influence. At 28 days, the effect of all three parameters on compressive strength was found to be statistically insignificant ($p > 0.05$), although cement continued to contribute the highest share of variance.

For other performance indicators such as dry unit weight, water absorption, capillary water absorption, thermal conductivity, and sound transmission, no statistically significant relationships were detected at the 95% confidence level. However, the weight loss under high-temperature exposure was strongly influenced by PET content ($p < 0.05$), while compressive strength loss at $600\text{ }^\circ\text{C}$ was mainly affected by cement and pumice/bottom ash ratios. In addition, the cost and $\text{CO}_2\text{-e}$ emissions were significantly impacted by cement and PET contents, with cement showing the highest contribution to variance in both cases.

Overall, the statistical validation confirms that cement content is the dominant factor across most performance properties, followed by the pumice/bottom ash ratio, whereas PET shows significant influence primarily under high-temperature and cost-related parameters. These results highlight the robustness of the experimental design and provide confidence in the optimization outcomes.

4. General

S/N ratios for the Taguchi performance characteristic were calculated from test results and expressed in decibels (dB) [81]. In the Taguchi design, all parameters were assigned

equal impact values of 100%, and average S/N values for performance metrics were computed. Table 9 summarizes the mixture results based on the calculation data, under this equal impact assumption, considering varying ratios of cement, pumice/bottom ash, and PET.

Table 9. The average S/N ratio values of the material scenario with equal percentage impact used in determining the overall performance of the samples.

Mixture No	S/N Values (dB)									Impact Per. (%)
	1	2	3	4	5	6	7	8	9	
Compressive Strength (28 days)	14.27	16.88	14.51	14.4	17.23	15.69	18.58	21.70	20.06	11.11
Dry Unit Weight	−2.41	−2.48	−2.28	−2.57	−2.50	−2.57	−2.67	−3.29	−3.39	11.11
Water Absorption	−25.13	−24.48	−24.16	−22.90	−24.32	−26.34	−23.19	−21.75	−19.90	11.11
Capillary Coefficient	−35.61	−36.22	−38.63	−37.11	−38.38	−36.58	−36.08	−36.87	−33.62	11.11
Thermal Conductivity	31.16	28.16	48.67	31.09	37.39	26.21	30.16	26.91	28.71	11.11
High Temperature Strength Loss	−32.55	−34.36	−35.65	−34.74	−36.96	−36.63	−35.32	−36.21	−37.51	11.11
High Temperature Weight Loss	−21.88	−23.39	−24.13	−23.09	−24.35	−21.80	−24.24	−21.22	−22.83	11.11
Cost	−57.08	−57.34	−57.60	−58.03	−58.24	−57.76	−58.87	−58.42	−58.65	11.11
Carbon dioxide Emission	−47.42	−47.08	−46.77	−47.99	−47.71	−48.27	−48.53	−49.07	−48.82	11.11
Average S/N	−19.62	−20.03	−18.44	−20.10	−19.76	−20.89	−20.02	−19.80	−19.55	100

Equal impact percentages were assumed for all parameters in calculating average signal-to-noise (S/N) ratios for performance statistics. Figure 14 illustrates the effect of the nine sample values on performance metrics based on these average S/N ratios.

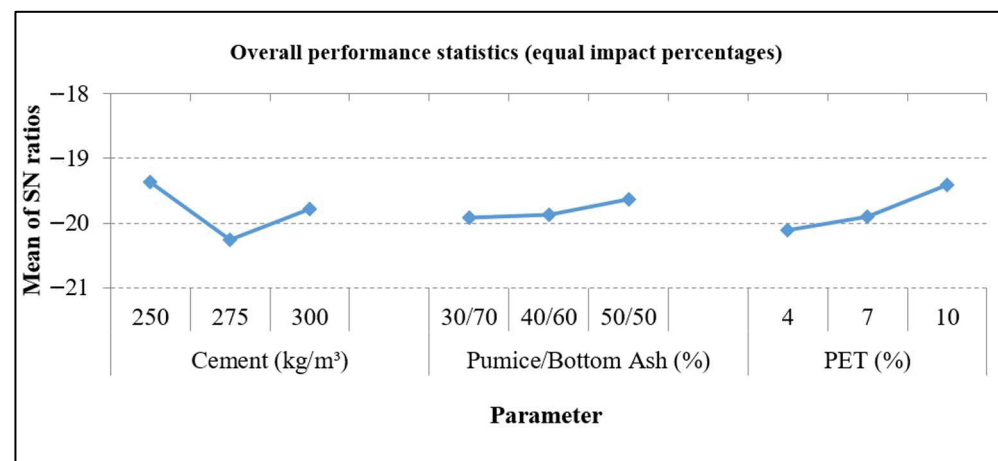


Figure 14. The effect of parameters on overall performance statistics (equal impact percentages).

Average S/N values for performance metrics were calculated by assigning varying impact percentages (out of 100) to the parameters in the Taguchi design. In the Taguchi method, weighting parameters according to the importance of the intended product is essential. In this study, the weights were set based on the significance of commercially available wall-building blocks. Table 10 presents the scenario results showing the impact percentages for variables such as cement, pumice/bottom ash ratio, and PET content.

Table 10. In determining the overall performance, the average S/N values for the different material scenario results with varying percentage impact ratios used in the samples are calculated.

Mixture No	S/N Values (dB)									Impact Per. (%)
	1	2	3	4	5	6	7	8	9	
Compressive Strength (28 days)	14.27	16.88	14.51	14.4	17.23	15.69	18.58	21.7	20.06	5.17
Dry Unit Weight	−2.41	−2.48	−2.28	−2.57	−2.5	−2.57	−2.67	−3.29	−3.39	15.52
Water Absorption	−25.13	−24.48	−24.16	−22.9	−24.32	−26.34	−23.19	−21.75	−19.9	8.62
Capillary Coefficient	−35.61	−36.22	−38.63	−37.11	−38.38	−36.58	−36.08	−36.87	−33.62	8.62
Thermal Conductivity	31.16	28.16	48.67	31.09	37.39	26.21	30.16	26.91	28.71	17.24
High Temperature Strength Loss	−32.55	−34.36	−35.65	−34.74	−36.96	−36.63	−35.32	−36.21	−37.51	8.62
High Temperature Weight Loss	−21.88	−23.39	−24.13	−23.09	−24.35	−21.8	−24.24	−21.22	−22.83	8.62
Cost	−57.08	−57.34	−57.6	−58.03	−58.24	−57.76	−58.87	−58.42	−58.65	15.52
Carbon dioxide Emission	−47.42	−47.08	−46.77	−47.99	−47.71	−48.27	−48.53	−49.07	−48.82	12.07
Average S/N	−18.77	−19.45	−16.36	−19.25	−18.54	−20.32	−19.49	−19.74	−19.35	100

The influence of varying parameter percentages on performance statistics, based on average S/N ratios, was analyzed. Figure 15 illustrates the effects of the nine sample values on these performance metrics.

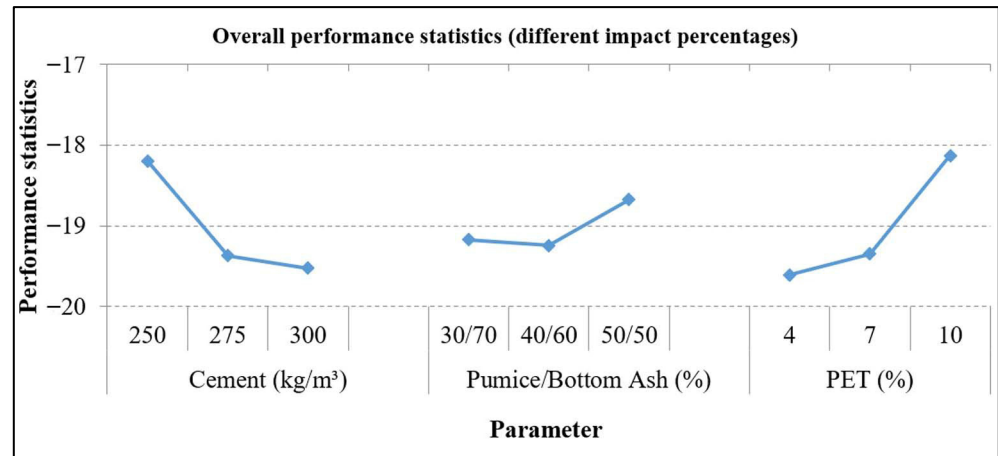


Figure 15. The effect of parameters on overall performance statistics (different impact percentages).

When examining Figures 14 and 15, one can observe that based on the statistical data derived from the test and analysis results, the optimal values—whether effect percentages are assigned equally or differently—are determined as follows: cement at 250 kg/m³, pumice/bottom ash ratio at 50/50, and PET content at 0.1%. A comparison with the experimental design data reveals that this combination corresponds to the type 3 sample. Accordingly, commercial-scale prototype production can proceed without additional validation experiments during the Taguchi design process.

The thermal conductivity, dry unit weight, water absorption, and compressive strength values of the optimum type-3 sample are compared with those of commercially available traditional block products in Table 11. It is noted that the values of the type-3 sample fall within the required ranges. Moreover, its compressive strength is significantly higher than

that of typical non-load-bearing wall blocks. Although it is less commonly used due to cost considerations, the sample exhibits lower water absorption and higher compressive strength compared to autoclaved aerated concrete blocks, which are generally preferred for their specific characteristics. The dry unit volume density values place the sample within the lightweight concrete class. These findings suggest that commercial production of building blocks using the developed mortar mixture is feasible.

Table 11. Comparison of commercial traditional blocks and optimum sample type-3 according to the standards (Created by the author).

Block Type	Dry Unit Weight (g/cm ³)	Compressive Strength (N/mm ² or MPa)	Thermal Conductivity Calculation Value(λ) (W/(m·K))	Water Absorption (%)
Horizontal Hole Brick [82]	min 0.50–max. 1.0	min. 2.0–max. 7.5	—	max. 15
* Horizontal Hole Brick [83]	min. 0.6–max. 0.7	min. 2.0–max. 2.5	—	—
Vertical Hole and Pressed Clay Brick [82]	min. 1.0–max. 2.0	min. 4.5–max. 22	—	max. 15
* Vertical Hole Brick [82,83]	min. 0.65–max. 1.1	min. 3–max. 14	min. 0.18–max. 0.50	—
Solid Mixing Brick [82]	—	min. 2.5–max. 5	—	max. 15
Perforated Mixing Brick [82]	max. 1.4	min. 2.5–max. 5	—	max. 15
Concrete Brick Cement Dosage 250 kg/m ³ Brick [82]	max. 1.6 for wall–max. 1.4 for slab	min. 2.0–max. 3.5	—	max. 20
Concrete Brick Cement Dosage 300 kg/m ³ Brick [82]	max. 1.6 for wall–max. 1.4 for slab	min. 4.0–max. 7.0	—	max. 20
Concrete Block Cement Dosage 200 kg/m ³ Brick [82]	min. 1.6	min. 5	—	max. 15
Concrete Block Cement Dosage 250 kg/m ³ Brick [82]	min. 1.6	min. 7	—	max. 15
Concrete Block Cement Dosage 300 kg/m ³ Brick [82]	min. 1.6	min. 9	—	max. 15
* Pumice [84]	min. 0.72–max. 1.28	min. 1.5–max. 5	min. 0.11–max. 0.50	—
* Autoclaved Aerated Concrete [85]	min. 0.30–max. 0.58	min. 1.5–max. 5	min. 0.082–max. 0.19	—
Type 3-Optimal Sample	1.3	5.96	0.27	16.1

* These are the specifications of the blocks presently marketed in Turkey.

5. Summary of Results

This study experimentally optimized composite mortars containing PET and bottom ash for lightweight, non-load-bearing construction applications. The main findings can be summarized as follows:

1. Compressive Strength: Increased with cement content (25.1% rise from 250 to 300 kg/m³). Optimal strength was achieved at a pumice/bottom ash ratio of 40/60 with 4% PET.
2. Dry Unit Weight: Rose with cement; maximum values observed at 30/70 pumice/bottom ash and 10% PET.
3. Water Absorption: Decreased with higher cement and pumice/bottom ash ratios. The lowest absorption was recorded at 7% PET.
4. Capillary Water Absorption: Lowest values were obtained at 300 kg/m³ cement, 50/50 pumice/bottom ash, and 7% PET.
5. Thermal Conductivity: Increased with cement but decreased with higher PET and pumice/bottom ash ratios. Increasing PET from 4% to 10% reduced conductivity by 38%.

6. High-Temperature Weight Loss: Increased with higher PET but decreased with higher cement and pumice/bottom ash ratios.
7. High-Temperature Strength Loss: Lowest at 50/50 pumice/bottom ash, reducing strength loss by 7% compared to 30/70.
8. Cost Analysis: Costs increased with cement and PET content but were only minimally affected by pumice/bottom ash ratio. Cement increase from 250 to 300 kg/m³, raised cost by 2.5%.
9. Carbon Emissions: Rose with cement but decreased with PET. Cement increase led to a 3.5% rise in emissions.
10. Optimum Mix: Type 3 (250 kg/m³ cement, 50/50 pumice/bottom ash, 10% PET) showed the most balanced performance.
11. Performance: The optimum mix reached 5 MPa compressive strength, dry unit weight of 1.3 g/cm³, water absorption of 16.1%, and thermal conductivity of 0.27 W/(m*K), making it suitable for lightweight construction.
12. Energy Efficiency: Production required less energy compared to conventional block manufacturing.
13. Sustainability: The process enables recycling of its own waste, reduces raw material demand, and contributes to a circular economy approach.

6. Conclusions

The experimental results confirm that PET–bottom ash composites can provide an eco-efficient alternative for lightweight construction. The proposed mix achieved a compressive strength of 5 MPa, thermal conductivity of 0.27 W/(m*K), and dry unit weight of 1.3 g/cm³, fulfilling the technical requirements for facade panels, interior partition walls, ceilings, and floor systems.

Beyond technical performance, the material demonstrated lower carbon emissions and production costs compared to conventional blocks, while incorporating post-consumer plastics and industrial by-products. This supports Sustainable Development Goals (SDGs) such as SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

The findings align with previous studies on PET-based composites, yet show improved performance in terms of strength, thermal conductivity, and sustainability, highlighting strong potential for market adoption. Importantly, the material can be produced on pre-cast lines with minimal process adaptation, offering a scalable solution for reducing the construction industry's environmental footprint.

7. Limitations and Future Work

This study has certain limitations that should be acknowledged. Although the experiments were conducted using a specially designed press machine simulating industrial conditions, the results are still limited to pilot-scale production and have not yet been validated on a large industrial scale. In addition, freeze–thaw resistance and outdoor weathering tests were not performed, which are critical for assessing long-term durability. The cost analysis presented is informative; however, the results could vary depending on fluctuations in large-scale PET supply or changes in energy prices. Furthermore, no full life cycle assessment (LCA) was conducted, and analyses such as carbon and water footprints should be performed in collaboration with professional organizations for a more comprehensive environmental evaluation.

Future research will aim to address these limitations by including extended curing periods, freeze–thaw cycles, outdoor weathering, and validation under industrial-scale production conditions. Moreover, professional LCA studies will be incorporated to evalu-

ate the overall environmental impact. Although this study mainly focused on short-term performance, future investigations will also consider strength retention at higher temperatures (800 and 1000 °C), further validating the stability and applicability of PET–bottom ash composites in real service conditions. Additionally, dedicated analyses of indoor air quality—including VOC release, potential leaching of microplastics, and compliance with healthy building standards—will be performed to ensure that PET–bottom ash composites are safe and suitable for long-term indoor use.

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Abbreviations

The following abbreviations are used in this manuscript:

PET	Polyethylene Terephthalate
SDG	Sustainable Development Goal
MPa	Megapascal
dB	Decibel
g/cm ³	Gram per cubic centimeter
kg	Kilogram
kg/m ³	Kilogram per cubic meter
kN	Kilonewton
m ³	Cubic meter
mm	Millimeter
N/mm ²	Newton per square millimeter (stress or pressure)
Tf	Temperature difference (K)
W/(m·K)	Thermal conductivity unit
%	Percent
°C	Degrees Celsius
λ	Thermal conductivity coefficient (W/(m·K))
CO ₂	Carbon Dioxide

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